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PAPER C2

TURNING, MILLING, AND DRILLING WITH ABRASIVE-WATERJETS

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Summary

This paper addresses new applications for material removal with abrasive-waterjets (AWJs). Research studies were conducted to machine such materials as magnesium boron carbide, ceramics, titanium, glass, carbon/carbon composites, and other hard-to-machine materials. For the first application addressed, turning, the effects of different parameters on the machining results (such as the volume removal rate and waviness) were determined. The experimental data and methods of surface finish improvement with AWJs are presented. It was found that surface finish can be controlled; however, an optimized strategy may be to combine AWJs for near-net-shape turning and diamond or ceramic tooling for final finishing. The second application addressed is milling with AWJs to produce three-dimensional cavities. Techniques of depth control machining are discussed. It was found that surface morphology is largely dependent on the abrasive particle size and the strategy of traverse. The final application addressed is the drilling of holes in different materials. Holes 0.5 mm in diameter and 30 mm long can be drilled in glass and laminated composites. Holes can also be produced by milling. This requires multiple-jet traverses over a sacrificial mask of hard material. Inspection of the machined surfaces revealed no adverse mechanical or thermal effects. A comparison with other nontraditional machining techniques is presented. This comparison indicates that AWJs represent an efficient material removal method.

Nomenclature

d_m	=	mixing tube diameter	p	=	waterjet pressure
d_n	=	waterjet orifice diameter	q_w	=	water flow rate
d_p	=	particle diameter	R_w	=	surface waviness
d_1	=	diameter before turning	s	=	standoff distance
d_2	=	required turned diameter	u	=	feed rate
d_3	=	final machined diameter	δ	=	lateral feed increment
m_a	=	abrasive flow rate	δ_a	=	actual depth of cut
N	=	rotational speed	δ_v	=	volume removal rate
N_a	=	number of increments	θ	=	angle of cutting
N_p	=	number of passes			

1. Introduction

New advances in materials technology have spawned a wide range of new materials and applications. These advances necessitate the development of compatible machining techniques, especially for hard-to-machine materials. Examples of newly developed materials are ceramics, ceramic composites, metal matrix composites, laminates, high specific strength materials, and fiber-reinforced resin composites. Many of these new materials are both hard and tough, which makes them difficult to machine. Conventional edge tool machining is often technically or economically inadequate for the machining of such materials. New nontraditional machining techniques are being developed to fill the gaps where conventional methods are inefficient. These new techniques employ different forms of mechanical, thermal, chemical, and radiation energy (1-4).

The AWJ technology is one of the most recent nontraditional machining methods to be introduced to the industry. It was first commercialized in 1983 for slotting and trimming applications. These applications include shape cutting of sheets, plates, and castings for a wide range of materials including glass, aluminum, steel, cast iron, titanium, and composites. It is estimated that over 400 AWJ cutting systems are now in use as production tools in factories.

This paper presents the results of studies using AWJs as tools for turning, milling, and drilling operations rather than slotting or trimming. The general background information is first given, followed by descriptions, data trends, and general observations for each of the turning, milling, and drilling operations. A comparison with other nontraditional machining methods is presented before the final conclusions are summarized at the end of the paper.

2. Background

AWJ systems for slotting, turning, milling, and drilling all consist of the same basic components, although the traverse system and catcher may be modified for specific applications. The following are the different components:

- high-pressure pump
- abrasive delivery system
- abrasive-waterjet nozzle
- traverse system
- catcher

High-pressure pumps are capable of continuously pumping water at pressures up to 400 MPa. These pumps are typically of the intensifier type. Medium-pressure pumps are both of the intensifier and crankshaft types. Their pressure range is up to 170 MPa. Typical water flow rates and power levels used in AWJ machining applications are 0.1 liter/s and 40 kW, respectively.

The abrasive delivery system consists of a storage hopper, a flow control valve and a feed tube. An abrasive feed rate of up to 10 g/s is typical in high-pressure AWJ machining applications. Abrasive mesh sizes of 60 to 150 are typical. For most applications, the hopper is located within 10 meters of the cutting nozzle for consistent flow of abrasives.

AWJs are formed in a nozzle system as shown in Figure 1. Pressurized water is expelled through a sapphire orifice to form a coherent, high-velocity waterjet (5). The waterjet and a stream of solid abrasives are introduced into a hard-material mixing and accelerating tube. A focused, high-velocity abrasive-waterjet exits the accelerator nozzle and performs the cutting action. Typical cutting results are given in Table 1.

The type of traverse system used with an AWJ depends on the application and the accuracy requirements. Multiaxis robots are often used in the aerospace and automotive industries. Optical X-Y tracing systems are used in glass and sheet metal cutting. In AWJ turning, a rotary device will be added to the traverse system. Manual manipulation of the jet or the workpiece is also used in rough trimming applications.

To catch the jet and material cuttings, a collecting tank is usually employed for slotting applications. Tube catchers have also been used for some applications with space restrictions. Ball-filled catchers are maneuverable and have been used for robotic cutting applications (6). Catchers for AWJ milling and turning systems should allow workpiece inspection as well as environment control. Such systems are now under development.

3. Turning

3.1 Process description

Turning with AWJs is similar to turning with a conventional single point tool on a lathe. A workpiece is rotated while the tool is continually fed parallel to the axis of rotation and incrementally fed toward the center of rotation. With AWJs, however, the jet can be moved in an X-Y-Z pattern with much larger lateral increments. Jet forces on the workpiece are negligible. The material that the jet sweeps is converted to very fine debris, contrary to chip formation in conventional machining. Figure 2 illustrates this process. The parameters of AWJ turning are:

a) Independent parameters

- waterjet pressure (p)
- abrasive particle size (d_p)
- mixing tube length (l_m)
- feed rate (u)
- standoff distance (s)
- diameter of workpiece (d_1)
- rotational speed (N)
- lateral feed increment (δ)
- waterjet orifice size (d_n)
- abrasive material
- mixing tube diameter (d_m)
- number of passes (N_p)
- jet angle (θ)
- required diameter (d_2)
- direction of rotation (+) (-)
- number of increments (N_a)

b) Machining results

- actual depth of cut (δ_a)
- geometrical characteristics
- metallurgical characteristics
- machined diameter (d_3)
- mechanical characteristics

3.2 Experimental results and observations

The data generated on a feasibility study of turning with AWJs are presented below along with data and observations on surface finish improvement.

3.2.1 Volume removal and surface waviness

The effect of feed rate on surface waviness is shown in Figure 3 for both aluminum and magnesium boron carbide Mg/B_4C metal matrix composite (ZK60A matrix-reinforced with nominally 15% B_4C). The data are for single-pass-turning of rods from 25.4 mm to 6 mm in diameter. Note that the volume removal rates in magnesium boron carbide are lower by about 38% than those in aluminum to obtain the same waviness. With conventional machining, however, the machining of Mg/B_4C is much slower than aluminum (by a factor of about 5 to 10).

The effect of waterjet pressure on surface waviness for Mg/B_4C is illustrated in Figure 4. Higher jet pressures will generally produce smoother surfaces and higher material removal rates; however, the sensitivity of surface finish parameters to other variables will be greater. For example, unsteadiness in feed rate or abrasive flow rate will be more critical at high pressures. Figure 5 shows additional data on the effect of pressure at different feed rates. The specific energy is also plotted on the same figure. The specific energy is naturally higher for higher pressures and lower feed rates at a fixed lateral feed increment (or volume removal). Consequently, minimization of the specific energy to obtain a certain finish requires an optimum combination of pressure and feed rate.

The rotational speed has been found (7) to be insignificant in affecting turning results, at least between 400 and 2500 rpm. This result implies that the accuracy of rotation is not a critical factor when turning with AWJs. The direction of rotation, however, was found (7,8,9) to affect both the material removal rate and the waviness of produced surfaces. These parameters improve when the workpiece is turned "away" from the jet rather than "toward" it.

Figure 6 shows an example of the effects of lateral feed increment and feed rate on surface waviness by machining Mg/B_4C rods to 6 mm in diameter, starting from 20 mm diameter in one case (a) and with 12.7 mm in another case (b). A direct comparison between the two cases is given in Figure 6 at a feed rate of 0.17 mm/s. Note the significant reduction in surface waviness with the reduced initial diameter due to the reduction in volume removal rate. If the feed rate is increased from 0.17 to 0.25 for case (b) to obtain a comparable volume removal rate to case (a) at a feed rate of 0.17 mm/s, the surface waviness will also be comparable.

The shadowgraphs in Figure 7 show turned aluminum surfaces for different multiple lateral increments but for the same total lateral feed (3.048 mm). The figure illustrates that a reduced increment size with an increased number of increments produces smoother surfaces. The contour shown with $N_a=12$ is closest to the required shape dimensions. It should be mentioned that, in this case, the total machining time is proportional to the number of increments. The shadowgraphs in Figure 8 illustrate the effects of varying the water and abrasive flow rates

The repeatability of the AWJ turning process depends on the control and steadiness of many factors. For example, a repeatability range in waviness of 60 to 90 microns was observed for the following ranges of variation for several parameters:

- pressure : ± 2 MPa
- feed rate : ± 8 to 20%
- abrasive flow rate : ± 0.05 g/s
- rotational speed : ± 80 rpm

3.2.2 Finishing of turned surfaces

To finish the turned surfaces, or reduce the waviness height, additional cutting passes need to be performed with different parameters. The following are strategies that can be used for surface finish improvement:

- a) Multipass finishing. Traversing the jet without lateral feed will result in surface waviness improvement. For example, the surface waviness of turned Mg/B_4C can be reduced from 122 to 64 microns with two additional passes.
- b) The use of finer abrasives with additional passes. Finishing tests conducted on aluminum, glass, and steel samples with different second-pass particle sizes indicated that this factor controls roughness rather than waviness. AWJ-machined glass surfaces subjected to additional finishing passes showed that semi-transparent surfaces can be achieved. This indicates that it is possible to achieve very low roughness values. However, the waviness of the surface did not significantly improve.
- c) Abrasive material. It was observed that finishing with softer abrasive materials (e.g., silica sand, copper slag) yields improved surface roughness. Again, no significant improvement was observed in surface waviness.
- d) Abrasive condition. Slurried abrasives have been found more effective in improving surface roughness. This may be attributed to the reduced impact velocity and to a possible improvement in the steadiness of abrasive flow.

Figure 9a shows machined profiles in Mg/B_4C with different finishing parameters. Table 2 lists the parameters of these tests. Figure 9b shows another example for aluminum. It can be seen that finishing with AWJs requires more passes, which increases the overall machining time. It may be more

control any splashing back of the jet.

Figure 17 shows a milled shape in aluminum. The produced shape reflects the changes in feed rate of the laterally oscillating jet. At the ends of the jet stroke, the depth is a maximum because the feed rate is a minimum. Observe the lay produced due to the overlapping of passes as the sample is fed normal to the jet oscillation plane.

A uniform-depth cavity can be milled if a uniform feed rate is used with a uniform exposure time of the jet over the material surface. One method to obtain a relatively uniform feed and exposure time is by masking the target surface with a hard material cut with the required pattern to be milled. The mask will only allow jetting in traverse zones where the feed rate is uniform. For example, an oscillatory nozzle motion can be "filtered" by the mask to eliminate the dwell at the end of travel strokes. Figure 18 shows a sample milled with this approach. A nozzle mounted on a robot arm was allowed to move back and forth at a feed rate of about 0.4 m/s. The nozzle was laterally indexed 0.25 mm after each pass. The lay of the produced surface indicates the direction of feed, contrary to turning where the lay is not evident.

4.4 Surface finish improvement

The strategy of milling with AWJs may include the use of different abrasive materials. The use of hard abrasives would be suitable for fast material removal rates. The use of soft abrasives may be suitable for finishing. When silica sand was used to finish a milled cavity and improve the depth uniformity, no positive results were gained. On the contrary, the depth variation increased after a few passes. The use of glass beads gave similar results to those of silica sand. It is concluded that depth uniformity control should be planned at the beginning of the milling process. Irregularities produced by one pass or traverse are not corrected in the subsequent passes but rather exaggerated. A different pattern of traverse on every pass will complicate the milling process.

Another strategy for finishing is to employ finer particles. Tests were conducted to finish a machined cavity with garnet sand (mesh 80) then finish it with garnet mesh 150. The cavity produced was compared to another produced by using only garnet mesh 150. The result is shown in Figure 19.

A number of materials were milled to determine their response to milling parameters. Data of single-pass nonthrough-cutting correlate well with multi-pass multi-increment milling results. Figure 20 shows volume removal rates for some materials.

5. Drilling

5.1 Process description

Hole drilling can be accomplished with one of the following methods:

- a) Piercing with a stationary AWJ. This is suitable for small-diameter holes.
- b) Kerf cutting by jet or sample circular traverse. The nozzle or material is either translated or rotated. A starting hole may be required in some cases. This method is suitable for hole diameters greater than the jet diameter.
- c) Milling of holes. A template mask of hard material may be used.

In this section we discuss observations on all of the above methods.

5.2 Hole piercing

Techniques of hole piercing with AWJs depend largely on the target material. In this section, the discussion will be focused on glass, as it represents brittle materials which are hard to drill.

economical to finish turned surfaces with conventional diamond tooling. Detailed studies on hybrid AWJ-conventional turning methods are being conducted.

Figure 10 shows ring grooves machined in a ceramic fiber-reinforced piston crown. Because garnet, the abrasive material used, is softer than the machined ceramic, a relatively smooth surface was obtained. The total groove machining time for the 76-mm-diameter piston was about 50 seconds. Again, a hybrid AWJ-diamond tooling method may be economically and technically optimized for this application.

It can be summarized here that, with reduced particle sizes, the use of soft abrasives, and an increased number of finishing passes, improved roughness can be achieved. The surface waviness, however, can only be slightly improved and requires better control over the steadiness of AWJ near-net-shape machining parameters, particularly the feed rate.

4. Milling

4.1 Process description

The basic problem of AWJ milling is to produce a cavity with controlled depth. In conventional milling, this depth is geometrically determined by the feed of the tool. With an AWJ (or any stream-like tool) the mechanics of the jet-material interaction process is the depth-determining factor. Many parameters control this interaction process and, accordingly, the milling results. To control the penetration of the jet, the energy that exits the material in slotting applications (to a catcher) needs to, somehow, be addressed. Figure 11 shows a simplified milling shape illustrating the quantitative and qualitative milling requirements.

In the following, single-pass kerf milling is first discussed. The coverage of an area with pattern overlapping or multitraverses will then be discussed.

4.2 Single-pass kerf milling

4.2.1 Surface uniformity

Inherent to the AWJ nonthrough cutting process (or that of any stream-like cutting tool) is the production of kerfs with irregular depths as shown in Figure 12. This irregularity is sensitive to many parameters, such as the angle of cutting, feed rate, and standoff distance (10,11). Figure 12 shows the effect of angle on the irregularity of depth produced. Note that the depth is maximized at about 80 degrees, but the surface irregularity is maximized at 100 degrees. The effect of feed rate is illustrated in Figure 13. At higher feed rates, the surface irregularity is reduced. Figure 14 shows the effect of standoff distance on the kerf depth uniformity.

4.2.2 Volume removal rate

The effect of impact angle on the surface removal rate for a depth of 0.127 mm is illustrated in Figure 15. It is well known (12-14) that, for ductile materials, shallow impact angles produce maximum volume removal. It has been observed, however, that brittle materials such as glass exhibit a similar response to the angle of cutting as ductile materials. An investigation on the effects of angle of impact is currently being conducted.

Figure 16 shows the effect of standoff distance on volume removal for mild steel. From this figure it can be seen that there are optimum standoff distances for maximum volume removal rates. An increased standoff distance, which results in the exposure of a larger portion of the surface to the jet, is associated with a decrease in volume removal.

4.3 Shape milling

Samples to be milled were placed in a catcher tank. A rubber shield was fastened to the nozzle to

Figure 21 shows traces of a jet-glass interface at different intervals (expressed in frame numbers). The penetration rate decreases significantly as the depth increases. This is attributed to the effect of the return flow, which reduces the particle velocity and interferes with the impact process. The average penetration rate in glass over the 100-mm hole depth is about 1.78 mm/s. Observe that the initial penetration rate is about 30 mm/s. The initial penetration rate when glass is cut rather than pierced is about 72 mm/s at the same jet parameters illustrated on Figure 21.

The most commonly used method for glass piercing is to employ relatively low pressures (about 30 to 40 MPa). The pressure is raised after piercing if cutting is to follow so that more efficient conditions are used for cutting. The disadvantages associated with this approach include low drilling rates, limited hole depth, and "weak" suction capability of the jet resulting in either inconsistent or limited abrasive flow.

High-pressure (200 to 400 MPa) piercing of glass using quick-acting on/off valves will result in glass fracture or cracking due to one of the following modes:

- fracture upon impact due to the shock loading of water
- cracking due to hole hydrodynamic pressurization or "hydro-fracking"

Methods of reducing the shock loading of the waterjet impact are necessary. Hole pressurization can be reduced by ensuring the continuity of the abrasive flow and by reducing the water flow rate.

Figure 22a shows a magnification of a hole pierced in glass. Observe the chipping and the "blasted" appearance near the hole entrance. At the exit side of the hole, chipping is also observed, as shown in Figure 22b. As the jet approaches the end of the hole, bending stresses near the hole area will result in non-erosion-created flakes. Figure 23 shows another phenomenon associated with hole drilling. It shows a relatively unblasted ring around the hole and a blasted zone outside of this ring. This secondary blasted zone is created by the abrasives reflected off the bottom surface of the AWJ mixing tube. The secondary blasted zone can be eliminated by chamfering or reducing the AWJ mixing tube diameter. High-quality holes can generally be produced by reducing particle size and eliminating the above-mentioned factors.

Hole shapes are greatly dependent on jet structure, target material, and standoff distance. The sensitivity to jet structure increases as material resistance to drilling increases. For example, holes drilled in tungsten carbide may have a kidney shape which suggests that the distribution of abrasives in the jet is not uniform. When the mixing tube length was increased from 35 mm to 70 mm (to improve mixing of abrasives and water), hole uniformity improved. Figure 24a shows the bell shape of a hole produced with a jet at a large standoff distance. Figure 24b shows a hole with a nominal diameter of 0.635 mm; observe the diameter variation with depth, as was seen in the graph in Figure 21. The difficulty of controlling the hole diameter uniformity increases as hole length increases. However, for relatively short holes, the dwelling time after drilling through is an important parameter for diameter control.

5.3 Hole trepanning

Hole cutting starts with either piercing or with a predrilled hole. The jet moves to the perimeter of the hole and preferably approaches it at a very shallow angle. The jet deflection significantly affects the uniformity of the surface waviness of the produced hole wall. The strategy that is often used is to reduce the feed rate such that the cutting interface is steady.

5.4 Hole milling

Hole milling can be accomplished by multipass traverses of a jet over the area to be milled. A template mask of more resistant material can be used to avoid complications with this jet traverse strategy. In this method, all hole material is converted to debris. Consequently, this method is not as efficient as hole cutting with AWJs. However, some advantages can be realized by hole milling:

- a) Small-diameter holes, smaller than the jet diameter, can be drilled.
- b) Hole edges are of uniform roughness.
- c) High accuracy and repeatability of hole diameters and positions are possible.
- d) A simple method for blind hole drilling is provided.

Figure 25 shows a sample of aluminum drilled with this method. It should be mentioned here that milling and cutting of holes can be combined together to achieve high drilling rates and high hole quality.

6. Comparison with other methods

In this section the AWJ is compared to traditional and nontraditional machining methods. These methods are illustrated in Figure 26. This figure shows typical ranges of power usage and typical ranges of volume removal rates.

Figure 27 shows the ranges of specific energy for the methods listed on the previous figure. Although Figures 26 and 27 indicate that the AWJ technique is among the most efficient methods, the use of the specific energy parameter for comparison is not appropriate. This is because many of these methods are not intended for the same application and not specifically for high volume removal rates. For example, a laser produces very narrow kerfs and consequently low volume removal rates. Also, USM is intended for slotting applications. A valid comparison will be related to a specific application or to a single machining operation. For slotting, a kerfing specific energy expressed as the energy required to generate a unit surface area (J/mm^2), would be a more accurate term for comparison. Another factor that should be considered for comparison is the requirement for additional finishing operations. For example, while a laser may cut some sheet metal faster than an AWJ, the removal of heat-affected zones is an additional operation that is not required for AWJ-machined surfaces. For some applications, the above-mentioned technologies may have technical and/or economic advantages over AWJs. However, AWJs appear to provide greater benefits for a wide range of machining operations. Among the general advantages of AWJ machining are:

- suitable for many operations such as turning, milling, and drilling
- ability to machine very soft and very hard materials
- ability to machine multimaterial composites selectively
- can cut stacks of different materials
- minimal deformation stresses
- no thermal effects
- reasonable material removal rates
- omnidirectional machining
- no heavy clamping needed for workpieces
- no direct "hard" contact with workpiece
- ideal for automation, robotics and remote control

7. Conclusions

The following conclusions can be drawn:

- a) Hard-to-machine materials can effectively be turned, milled, and drilled with AWJs. Examples of such materials are metal matrix composites (MMC), titanium, composites, glass, and ceramics. Complex external contours can be machined.
- b) High material removal rates can be obtained. For example, turning of a 25-mm-diameter Mg/B_4C rod to 6 mm in diameter can be accomplished in one pass at a feed rate of 0.12 mm/s. The jet power to achieve this is about 13 kW with 0.08 g/s of garnet abrasives.
- c) The AWJ is less sensitive to the type of material being machined than other methods such as a laser or EDM. For example, machining rates in aluminum are similar to those of Mg/B_4C MMC.

- d) The steadiness of the feed rate mechanism significantly affects the waviness of the turned surfaces. High feed rates result in reduced waviness of milled surfaces.
- e) The roughness rather than the waviness of the machined surfaces is most dependent on the abrasive particle size.
- f) Abrasive-waterjets may be used as near-net-shape turning or milling tools. Precision machining requires further efforts. A hybrid AWJ-conventional finishing method needs to be optimized.
- g) An optimum machining strategy will include parameter changes to maximize material removal rates and produce minimal surface irregularities. A method of in-place inspection of machined surfaces and control feedback systems needs to be developed.
- h) Machining with abrasive-waterjets is environmentally acceptable and safe, and it does not require extensive training. Automation will be preferred for the AWJ technique.
- i) Holes of 0.5 mm in diameter can be drilled in a wide range of materials, including glass and composites. The hole shape depends on the parameters of the AWJ and the drilling time. A typical drilling time in 25-mm-thick glass is 10 seconds for a 0.5-mm-diameter hole.
- j) Through and blind holes can be precisely milled using template masks of harder material than the target.

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Table 1. Typical maximum cutting feed rate* with AWJs for different materials

Material	Thickness (mm)						
	0.79	1.60	3.18	6.36	12.7	19.1	50.8
Carbon/carbon composites	42.3	31.7	22.3	13.5	7.50	4.20	0.85
Epoxy/glass composites	106	95.2	76.2	42.3	16.9	11.9	5.08
Graphite/epoxy composites	74.1	63.5	52.9	40.0	15.2	10.6	4.23
Kevlar (steel reinforced)	42.3	25.4	16.9	8.50	4.70	2.50	0.63
Glass plates	127	106	84.7	63.5	42.3	21.2	6.35
Aluminum	76.2	33.9	21.2	12.7	7.60	5.10	2.54
Carbon steel	29.6	21.2	12.7	7.50	3.10	3.39	1.27
Inconel	25.4	19.0	9.30	5.10	2.90	3.39	1.10
Stainless steel	27.5	19.0	10.2	6.80	4.20	3.54	1.21
Titanium	33.9	25.4	19.0	12.7	7.60	5.08	1.27

* feed rate is in mm/s

Table 2. Parameters of AWJ turning of the magnesium boron carbide samples shown in Figure 9

Test No.	Roughing, near-net-shape, and finishing parameters							
	Pass No.	w mm	p MPa	Grit type	Size mesh	m_a g/s	u mm/s	comments
F1	1	9.5	276	garnet	80	7.5	0.42	roughing pass
	2	0.127	207	garnet	80	6.0	1.27	near-net-shape
	3	0.00	138	garnet	150	3.0	1.27	finishing
F2	1	9.5	276	garnet	80	7.5	0.42	roughing pass
	2	0.127	207	garnet	80	6.0	1.27	near-net-shape
	3	0.00	138	garnet	150	3.0	1.27	finishing
	4	0.00	69	garnet	250	3.0	1.27	finishing
F3	1	9.5	276	garnet	80	7.5	0.42	roughing pass
	2	0.127	207	garnet	80	6.0	1.27	near-net-shape
	3	0.00	138	garnet	150	3.0	1.27	finishing
	4	0.00	69	garnet	250	3.0	1.27	finishing
	5	0.00	69	silica	398	3.0	1.27	finishing
F4	1	9.5	276	garnet	80	7.5	0.42	roughing pass
	2	0.127	207	garnet	80	6.0	1.27	near-net-shape
	3	0.00	138	garnet	150	3.0	1.27	finishing
	4	0.00	69	garnet	250	3.0	1.27	finishing
	5	0.00	69	silica	398	3.0	1.27	finishing
	6	0.00	69	glass	400	3.0	1.27	finishing

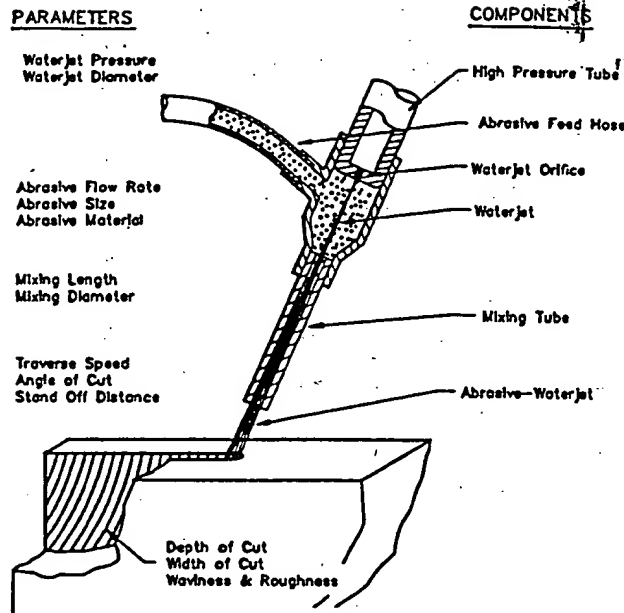


Figure 1: Abrasive-waterjet nozzle and parameters

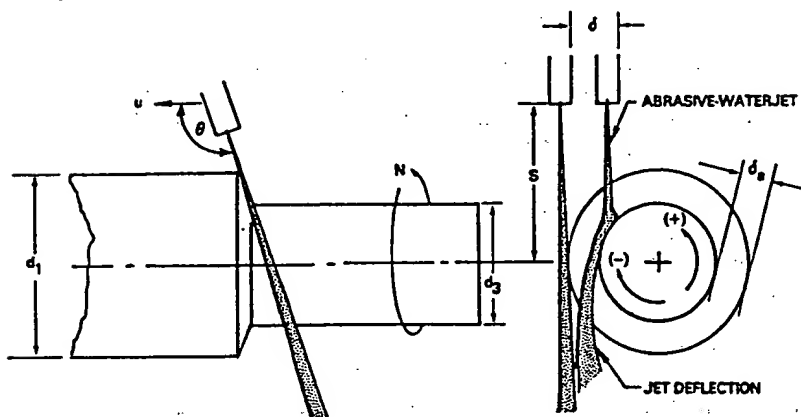


Figure 2: Geometrical parameters of abrasive-waterjet turning

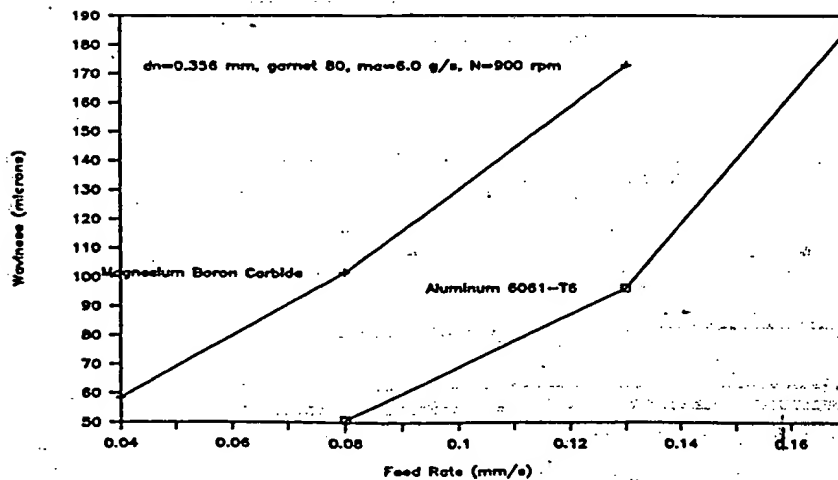


Figure 3: Effect of feed rate on waviness of turned surfaces for Aluminum and Mg/B_4C

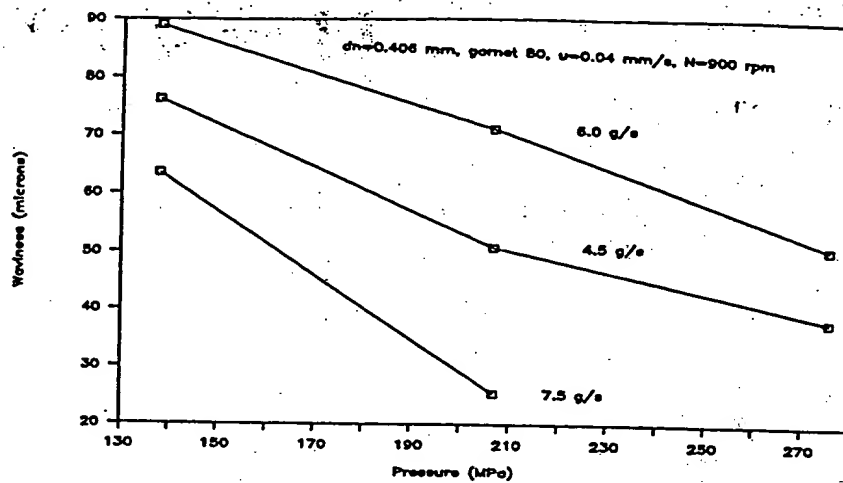


Figure 4: Effect of pressure and abrasive flow rate on waviness of turned surfaces of Mg/B_4C

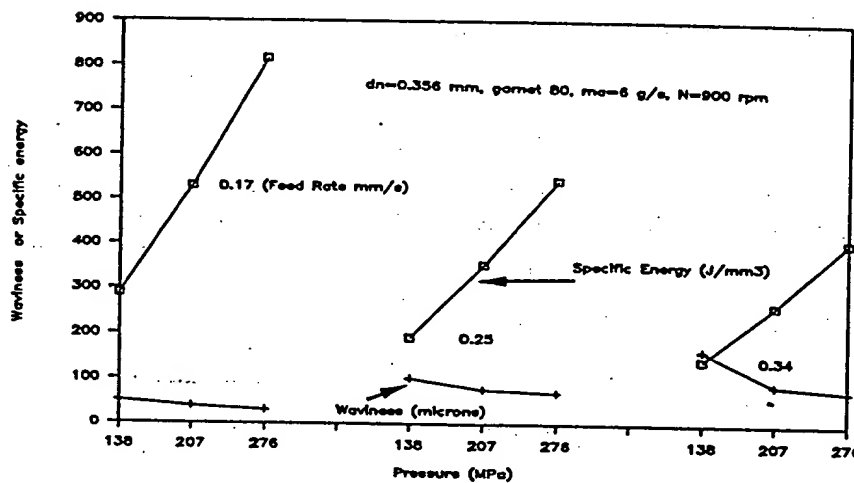


Figure 5: Waviness and specific energy of turned surfaces of Mg/B_4C at different pressures

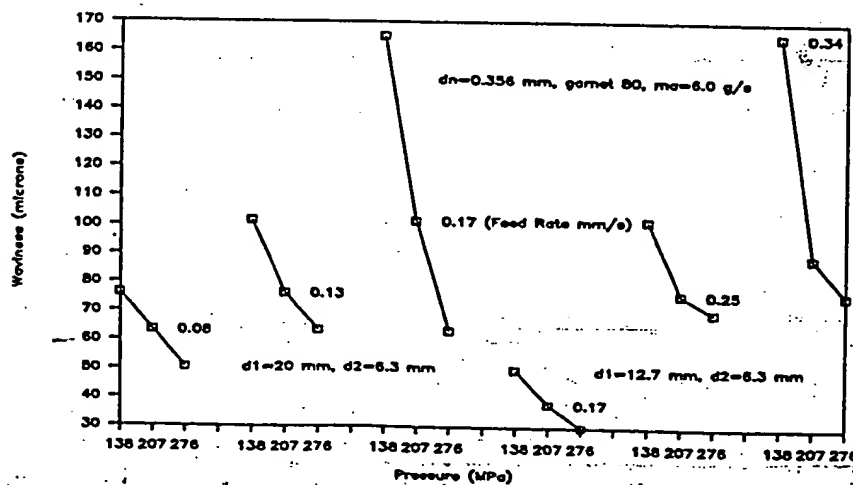


Figure 6: Effect of lateral feed increment on Mg/B_4C turned surfaces at different feed rates

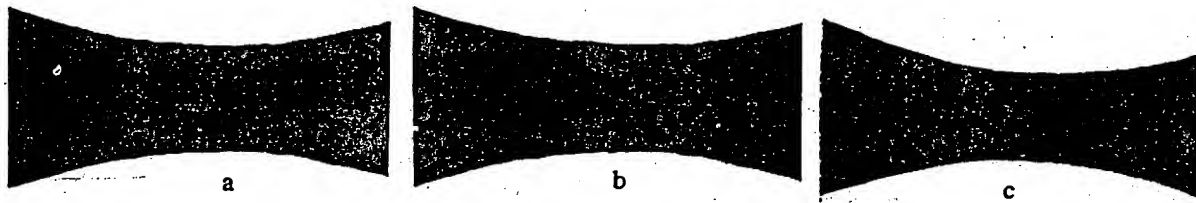


Figure 7: Shadowgraphs of machined aluminum showing effect of lateral feed increment

- a) $N_a=12$, $\delta=0.254$ mm, $R_w=15.2$ μ m
 b) $N_a=8$, $\delta=0.381$ mm, $R_w=25.4$ μ m
 c) $N_a=6$, $\delta=0.508$ mm, $R_w=38.0$ μ m

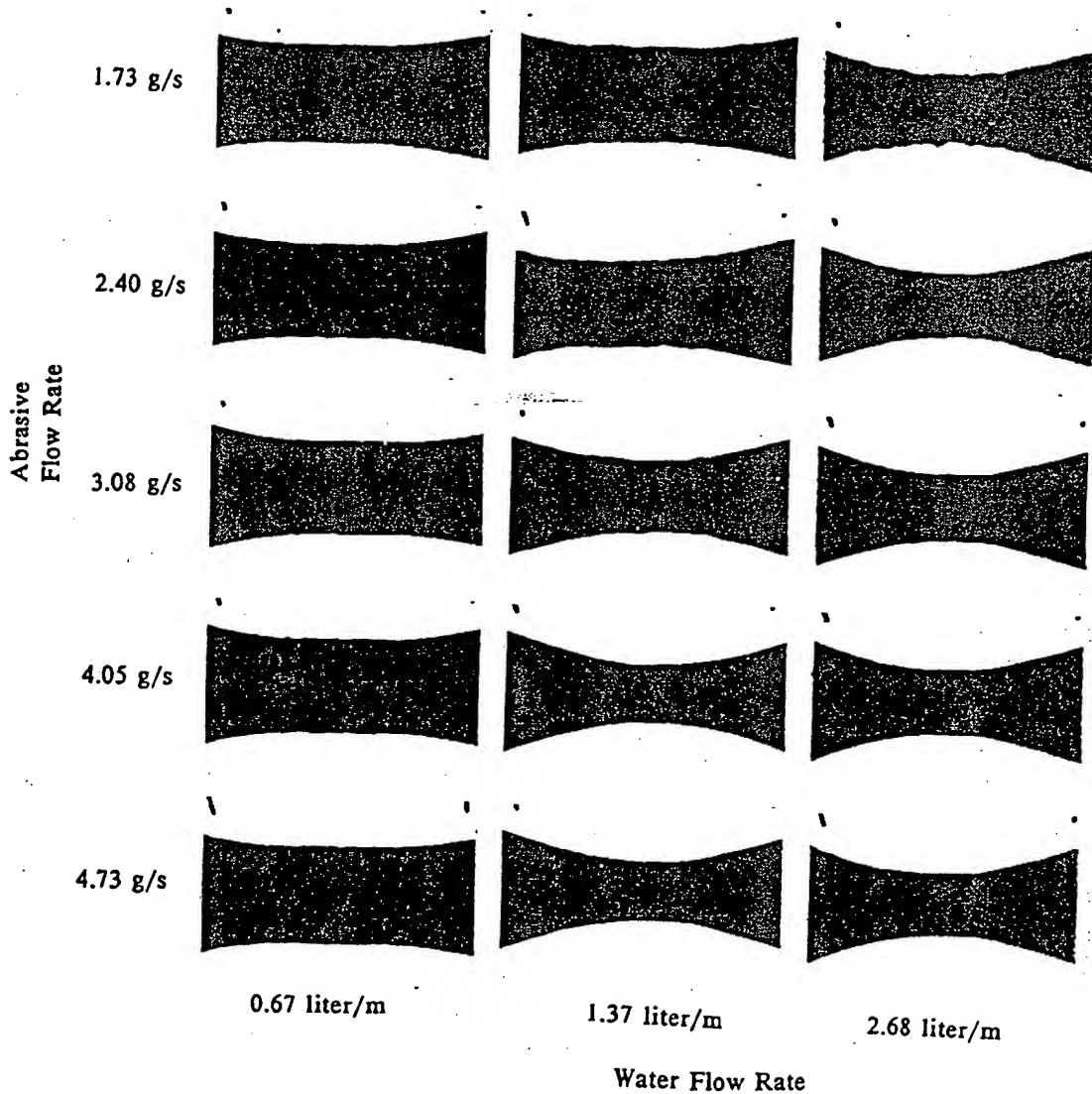
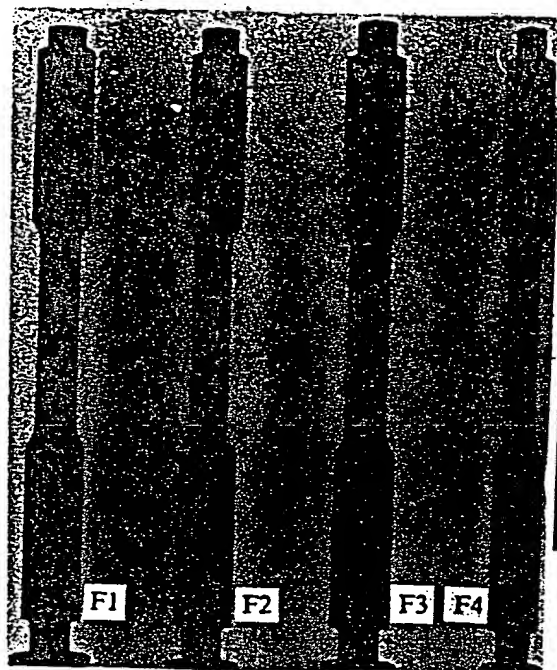
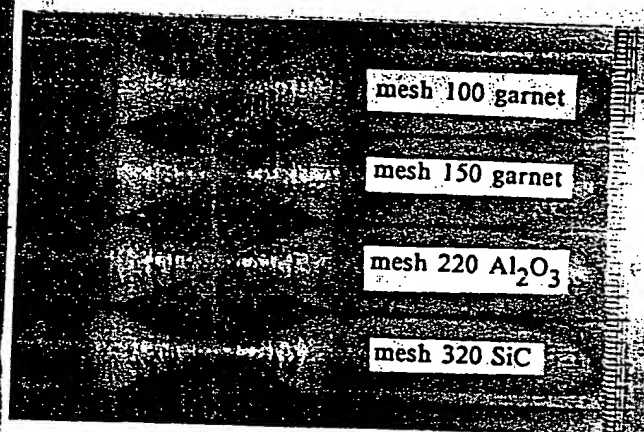


Figure 8: Shadowgraph of turned aluminum surfaces at different water and abrasive flow rates.

$p=207$ MPa, $u=2.54$ mm/s, $d_n=0.254$ mm, $m_a=0.07$ g/s mesh 80 garnet



a) Mg/B4C, see Table 2



b) Aluminum, roughing pass with garnet mesh 80.

Figure 9: Finishing with AWJs



Figure 10: AWJ-machined grooves in ceramic fiber reinforced piston crown

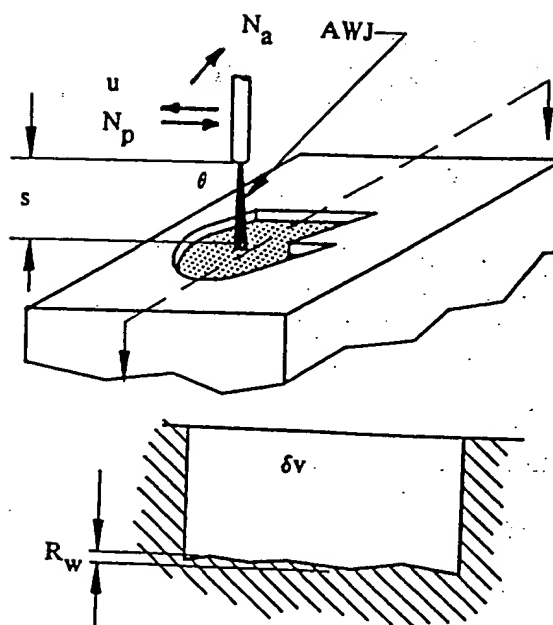


Figure 11: Geometrical parameters of AWJ milling

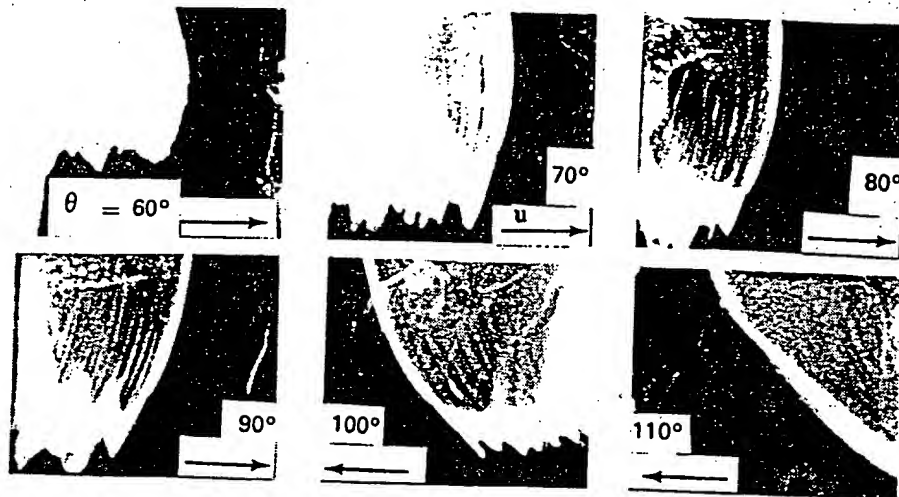


Figure 12: Effect of jet angle on uniformity of depth of cut in Plexiglas

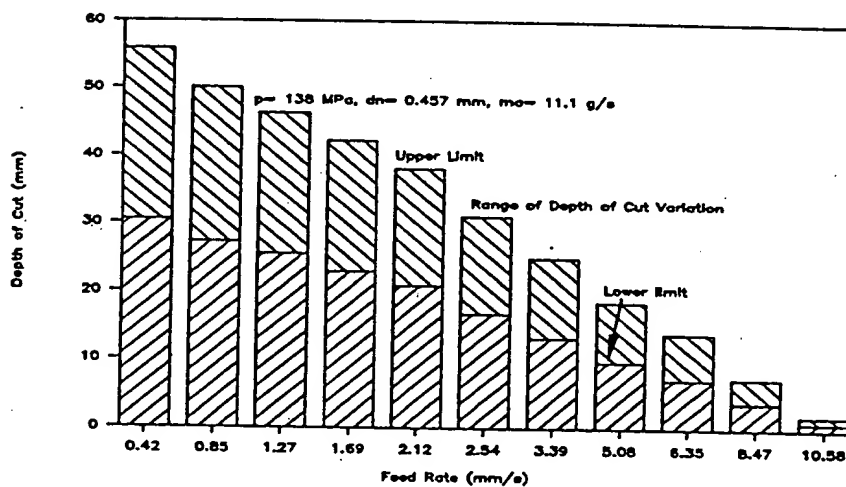


Figure 13: Effect of feed rate on depth of cut irregularity in mild steel

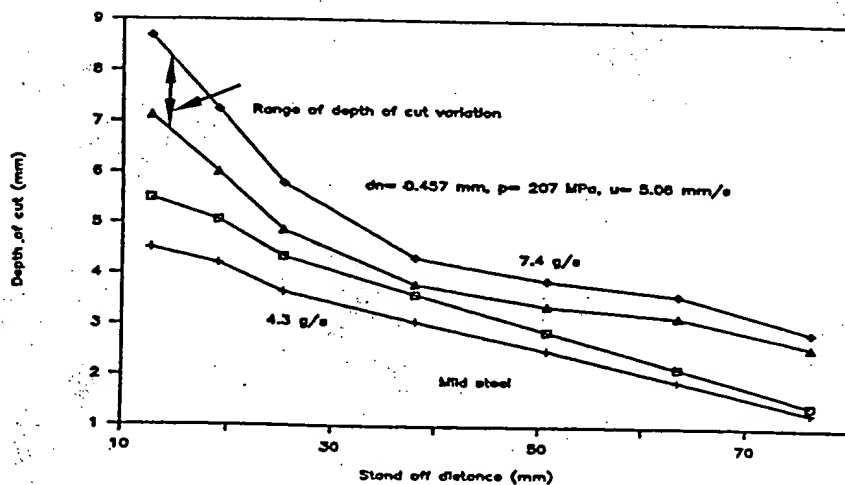


Figure 14: Effect of standoff distance on depth of cut irregularity

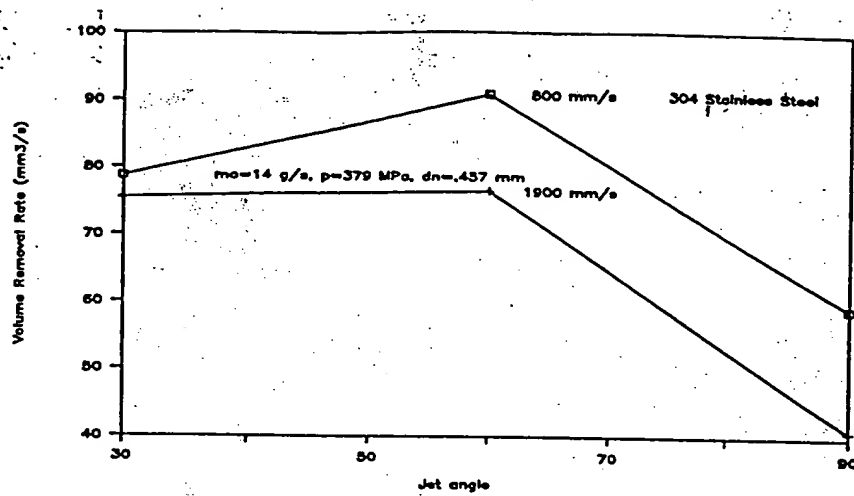


Figure 15: Effect of jet angle on volume removal rate

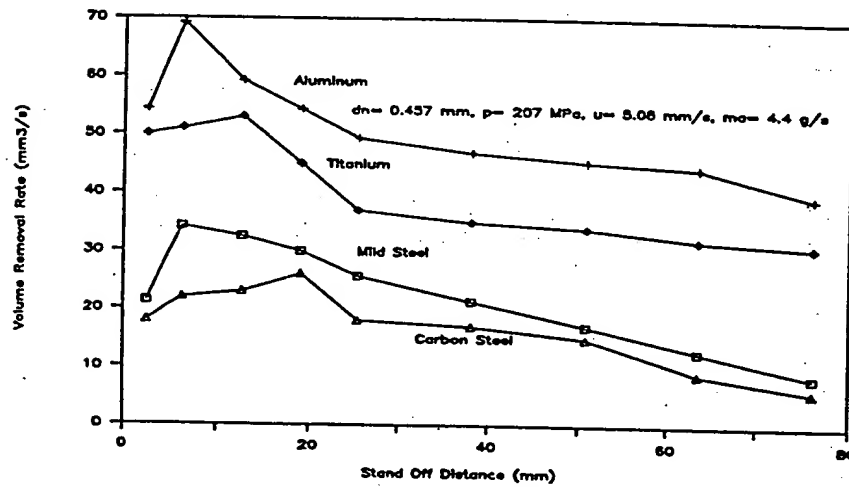


Figure 16: Effect of standoff distance on volume removal rate for different metals



Figure 17: Milled shape in aluminum with an oscillating AWJ



Figure 18: Milled shape in titanium using a steel mask

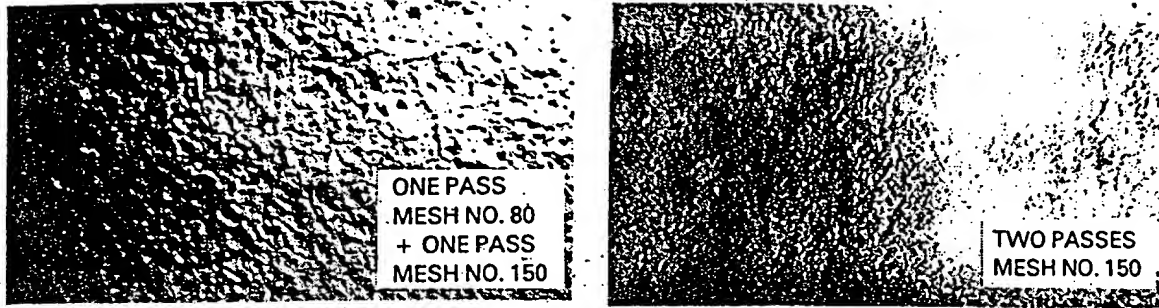


Figure 19: Effect of particle size on milled surface texture

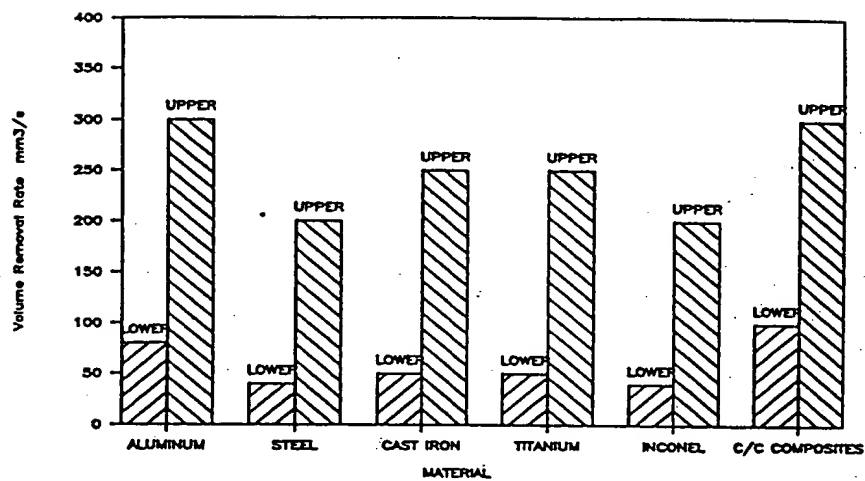


Figure 20: AWJ milling volume removal rates for some materials

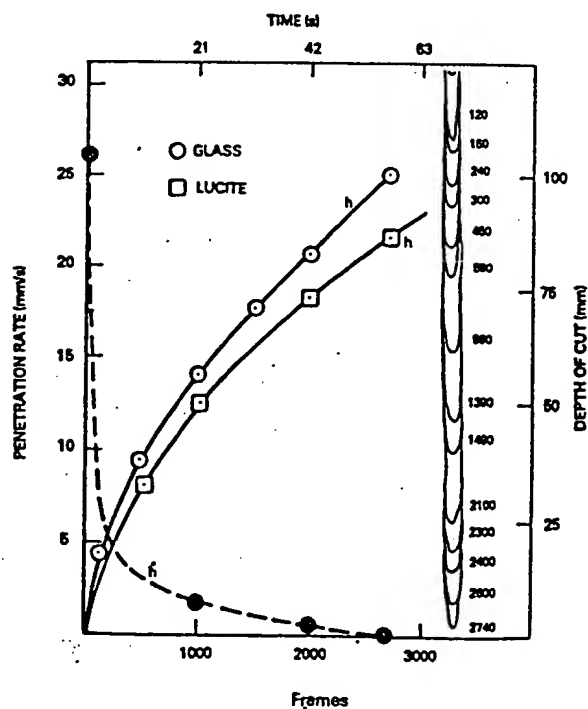


Figure 21: Hole drilling by piercing with AWJ

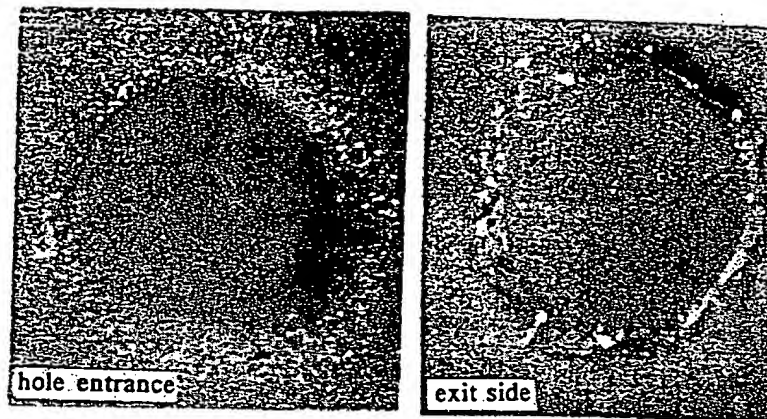


Figure 22: Blasting at hole entry and chipping at hole exit for glass piercing with improper AWJ conditions

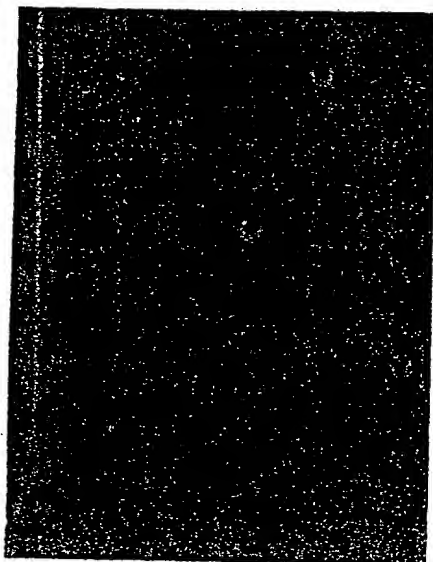


Figure 23: Outside ring blasted zone due to abrasive rebound off AWJ mixing tube

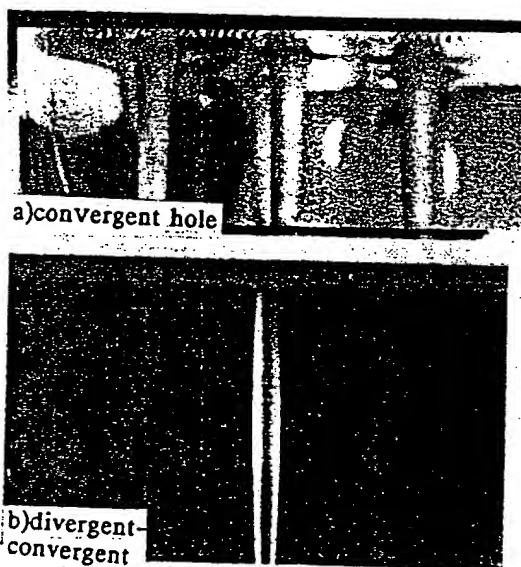


Figure 24: Hole shapes produced with AWJ piercing

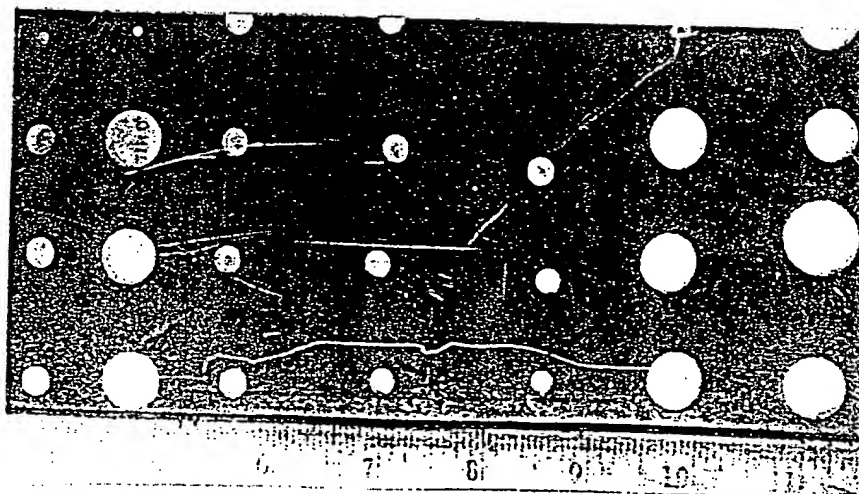


Figure 25: Milled holes in aluminum plate using a steel mask

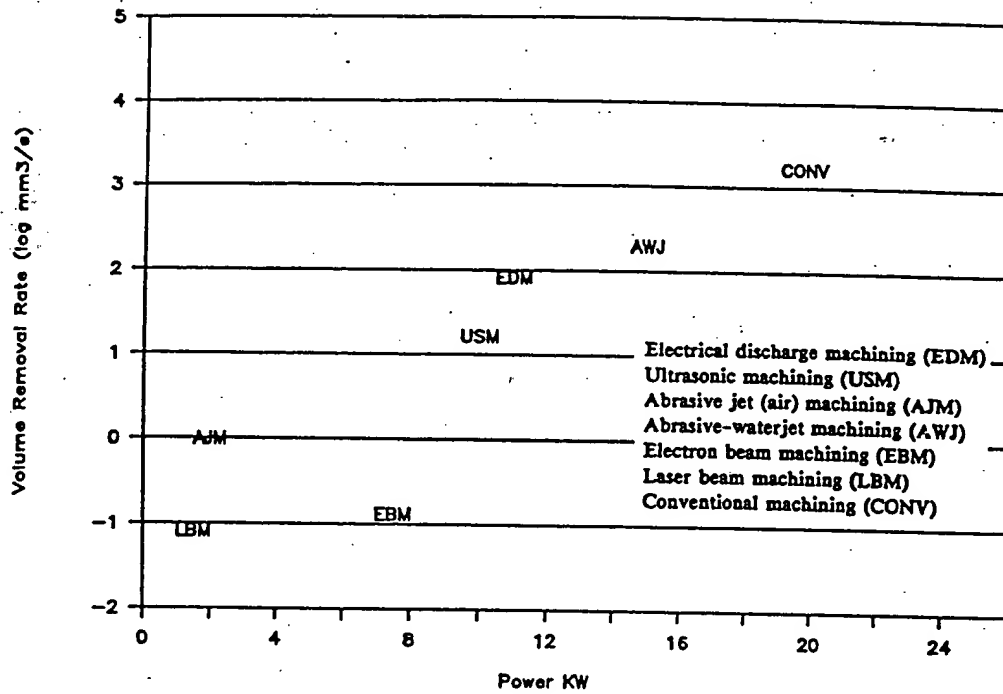


Figure 26: Power levels and typical volume removal rates of different machining methods

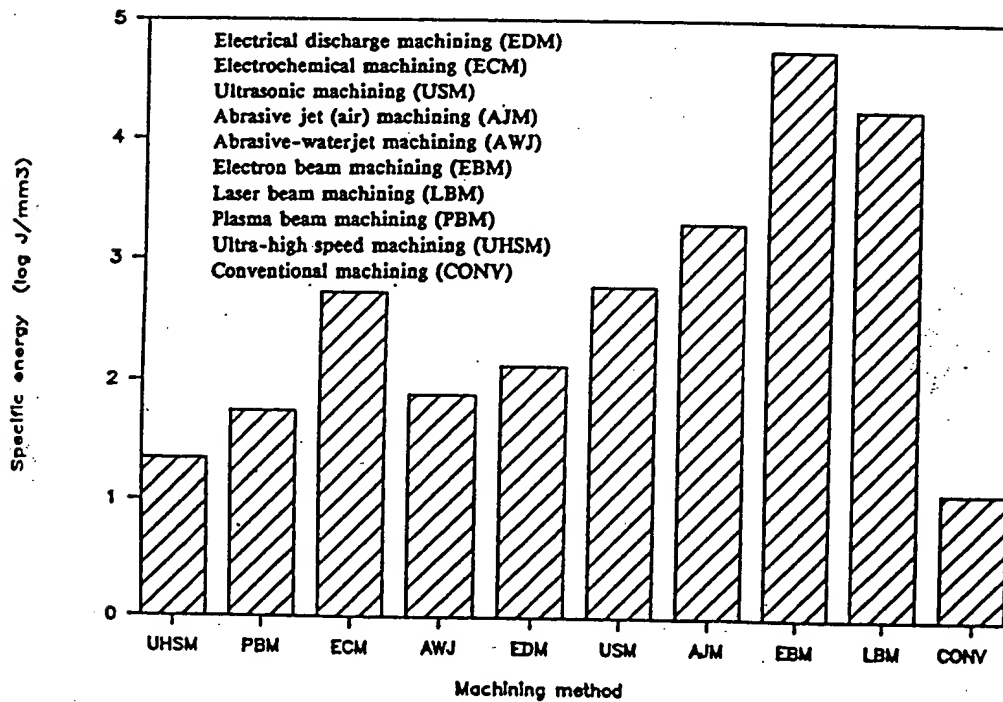


Figure 27: Typical specific energy for steel machining with different methods

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